Precision Solidification for Creating Multifunctional Material Systems

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Abstract: Transformation of our societies in the age of electrification and climate change increasingly demands metal manufacturers, including casting industries, to supply metallic-based materials, structures, and systems capable of integrating mechanical strength with other functionalities. This brief will focus on the pivotal roles that solidification-based technologies can play in meeting this challenge. By highlighting examples of relevant progress using near-net-shape and extreme-condition solidification processes, their potential to create multifunctional material systems through multi-materials and multi-technology approaches, will be explored.

Keywords: Foundry, casting, solidification, multifunctional materials, multi-processing,

1 Introduction

The 20th century witnessed significant technical advances in fluid dynamics, solidification sciences, and quality control through X-ray technologies. These advancements enabled the foundry industries to produce near-net-shape as-cast components, minimizing the need for extensive machining, thus optimizing both cost and energy efficiency. Recently, the imperatives of climate change and environmental preservation have accelerated transformative megatrends aimed at reducing carbon footprints. The shift towards miniaturization, electrification, renewable energy, and materials recycling across various domains requires the development of novel metallic-based components. These new components not only uphold traditional roles in providing mechanical strength but also integrate functionalities such as heat transfer, electron transport, energy conversion and harvesting, sensing, and adaptive responses to environmental variations.

These evolving demands require multilocational materials systems, characterized by complex chemistries, hierarchical microstructures at the nano-micro scale, and near-net-shape geometries. However, the manufacturing of these sophisticated materials poses significant challenges for traditional foundry processes. This presentation offers a brief overview of the challenges confronting the foundry industry and explores strategic approaches to advance casting processes to overcome these obstacles. The focus is on creating multifunctional materials systems that align with the rapidly changing landscape of technological, environmental, and societal demands.

2 Technologies

Solidification technologies highlighted in the presentation include planar flow foil casting, twin roll strip casting and stir casting. These processes are representative examples of non-equilibrium solidification conditions, near-net-shape features and multi-materials fabrication. The as-cast materials produced through the solidification routes can serve as feeds for other processing technologies, such as solid-state friction stir welding and friction stir additive manufacturing, realising sizes, geometries, structures and functionalities that solidification technologies alone cannot achieve. Furthermore, the role of digital technology, including artificial intelligence (AI) and machine leaning (ML), is highlighted for optimising either the operations of dynamic solidification processes or designing complex materials systems.

3 Discussion

The abilities of non-equilibrium solidification processes to generate a variety of atomic structures offers opportunities to induce functional properties while enhancing original structural properties. It is well established that near-rapid solidification of metal alloys at higher cooling rates, such as two roll casting (TRC) aluminium (Al) and magnesium (Mg) alloys [1][2], increases, for example, the concentration of alloying elements in the Al phase. The supersaturated Al phase alters atomic arrangement within ordered lattice structures, i.e. the unit cells repeating in 3D, resulting in significant increase in functional corrosion resistance [2]. With an extremely high cooling rate during rapid solidification, such as planar flow casting (PFC) as shown in Figure 1, this atomic orderly arrangement within the unit cell can be completely replaced by a random arrangement of atoms, leading to the formation of an amorphous metal [4]. This dramatic transformation of the unit cell from an orderly to a random atomic arrangement creates new functionalities [4] - [6]. For example, amorphous steel foils produced by planar flow casting exhibit superior soft magnetic properties [4] - [5], which have become the preferred materials choice for manufacturing modern electrical transformers and electric motors with high energy efficiency.

Resembling repeating atomic unit cells in a single-phase metal, metal matrix composites (MMCs) can be considered as consisting of large unit cells at the microscale with multiple phases, characterized by pseudo repeats of uniformly distributed phases. By carefully selection of these phases from different materials, MMCs with such pseudo unit cells can demonstrate unique functionalities that are not possible to achieve with the constituent materials alone. Stir casting technology has been demonstrated the most cost-effective technology to produce MMCs, including Al matrix composites (AMCs) with carbide (SiC) particles as enhancement. This multi-materials AMCs indeed exhibit advanced braking function in brake discs that neither Al nor SiC alone would possess [7].

Braking functionality of AMC-based brake discs, for example, involves converting the kinetic energy of moving vehicles into thermal energy through friction, followed by the subsequent removal of heat from the braking interfaces. This functionality replies on a complex interaction between various mechanical and functional materials properties, such as coefficient of friction, thermal conductivity, hardness and toughness. The key to optimising these interactions is the precise control of the multi-material phase distribution within the AMC pseudo unit cells. However, achieving this microstructural precision, particularly a uniform and hierarchical distribution of a high-fraction SiC particles, has been challenging for the stir casting process.

Microstructural optimisation of this SiC distribution in AMC multi-materials systems is achieved only when a multi-technology manufacturing approach is deployed. In this approach, Stir-solidified Al and MMC semi-finish parts are integrated using friction stir additive manufacturing [7]. This multi-materials and multi-technology method allows for precision control of the microstructures enhancing materials functionality in the final product. This increasing sophistication of performance requirement, materials and manufacturing methods predicts emerging development of digital technologies, such as artificial intelligence (AI) optimisation and machine learning (ML) modelling [8], as an integral part of future solidification-based materials technology.

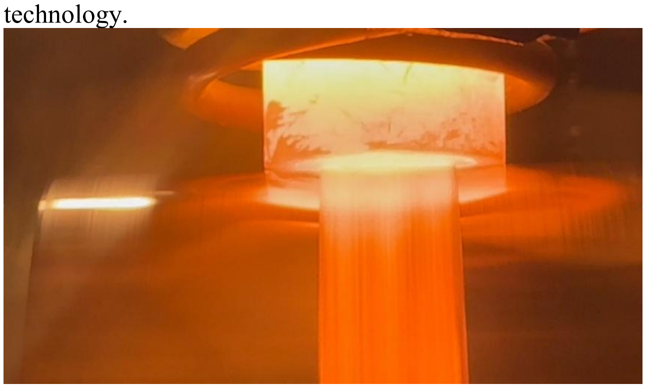

Fig.1 Planar flow casting

4 Conclusion

Solidification technology plays a pivotal role in emerging advanced manufacturing by integrating multiple materials through a multi-technology fabrication approach to meet increasing industrial demands. Precision control of solidification and microstructure, aided by AI optimization and ML modelling, is anticipated to be key for this technology to fulfill its critical role in the future.

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